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16. ABSTRACT

The paper presents a new model for predicting the particle collection performance of venturi scrubbers. It assumes that particles are collected by atomized liquid only in the throat section. The particle collection mechanism is inertial impaction, and the model uses a single drop collection efficiency equation based on the inertial impaction parameter. The model takes the form of an analytic expression for the particle penetration based on particle diameter and venturi scrubber parameters. No arbitrary empirical constants are used. A relation for the maximum throat length necessary for a venturi is also presented. The model is compared with experimental data from small- and large-scale venturi scrubbers.

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Venturi Scrubber Performance Model

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■ A new model for predicting the particle collection performance of venturi scrubbers is presented. The model assumes that particles are collected by atomized liquid only in the throat section. The particle collection mechanism is inertial impaction, and the model uses a single drop collection efficiency equation based on the inertial impaction parameter. The model takes the form of an analytic expression for the particle penetration based on particle diameter and venturi scrubber parameters. No arbitrary empirical constants are used. A relation for the maximum throat length necessary for a venturi is also presented. The model is compared with experimental data from small- and large-scale venturi scrubbers.

Venturi scrubbers are a type of gas-atomized spray scrubber. They employ gradually converging, then diverging sections. The venturi throat is the section between the converging and diverging sections. Liquid usually enters the venturi upstream of the throat through nozzles. Alternatively, the liquid may flow along the converging section walls until reaching the throat. At the throat the liquid is shattered into drops by high-velocity gas. Sometimes the liquid is introduced as preatomized drops at or before the throat through pressure nozzles.

Particle collection by liquid drops is the predominant occurrence in the venturi scrubber. Inertial collection, interception, diffusion, electrostatic collection, and gravitational collection are several of the mechanisms causing collection by drops. All investigators have concluded that inertial impaction is the principal mechanism of particle collection in a venturi scrubber for particles larger than 0.5 μm in diameter. For particles smaller than 0.1 μm. in diameter, diffusional collection prevails.

By performing a material balance for the dust over a differential scrubber volume with the assumption of constant liquid holdup, Calvert (*1, 2*) obtained a differential equation for the prediction of venturi scrubber performance. This equation for change in particle concentration is:

$$-\frac{dc}{c} = \frac{1.5|u_p - u_d|}{u_d d_d}\left(\frac{Q_L}{Q_G}\right)\eta dz \qquad (1)$$

Other investigators, such as Ekman and Johnstone (*3*), Morishima et al. (*4*), Dropp and Akbrut (*5*), Boll (*6*), and Behie and Beeckmans (*7*), have presented slightly different equations to describe the particle collection in a venturi scrubber. However, all of their equations can be transformed into Equation 1.

No analytic solution has been given to Equation 1. Yung et al. (*8*) have performed a numerical solution of this equation and presented graphical results. Calvert (*1*) and Calvert et al. (*9*) have integrated Equation 1 for constant throat diameter and an approximate drag coefficient relationship and obtained an explicit equation for predicting particle penetration. It involves an empirical constant that requires experimental evaluation. This paper presents a modification to Calvert's equation, which does not contain empirical constants.

Performance Model

Since most of the particle collection occurs in the venturi throat, we will apply Equation 1 to the throat section with the following simplifying assumptions:

- The flow is one-dimensional, incompressible, and isothermal.
- Particles are collected only by atomized liquid drops. The drop diameter is the Sauter mean diameter predicted by the empirical correlation of Nukiyama and Tanasawa (*10*). Although in actuality a distribution of drop sizes will exist, the use of a single representative size simplifies calculations and gives reasonable results.
- Liquid drops are uniformly spread across the duct, and the drop diameter is invariant with axial distance.
- There is no wall loss of liquid drops.
- At any cross section of the scrubber the liquid volume fraction is small.
- At the throat entrance, liquid drops have zero axial velocity.
- Drag coefficient is governed by the following relationship as suggested by Hollands and Goel (*11*):

$$C_D = (\text{constant})\, N_{Re}^{-0.5} = C_{Do}\left[\frac{u_{Go}}{|u_G - u_d|}\right]^{0.5} \qquad (2)$$

This relationship is adequate for Reynolds numbers ranging from 10 to 500. This is the range of Reynolds numbers of interest in venturi scrubbers. "C_{Do}" is determined from the "standard curve" using a Reynolds number calculated on the basis of the relative velocity applying at the throat entrance.

- Particle collection is primarily due to inertial impaction. We will use the simplified equation by Calvert (*2*) to estimate the single drop target efficiency

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$$\eta = \left(\frac{K_p}{K_p + 0.7}\right)^2 \tag{3}$$

where "K_p" is the inertial impaction parameter

$$K_p = \frac{C' \rho_p d_p^2 |u_p - u_d|}{9\,\mu_G d_d} \tag{4}$$

- Particles are flowing at the same velocity as the gas, i.e., $u_p = u_G$.
- The only force acting on the drops is the drag due to the relative motion of the gas and the drops. Thus, a force balance on the liquid drops gives

$$\frac{du_d}{dz} = \frac{3}{4}\frac{\rho_G}{\rho_L}\frac{(u_G - u_d)^2}{d_d u_d} C_D \tag{5}$$

Equations 1–5 are the governing equations for venturi scrubber performance. Equations 1 and 5 are nondimensionalized by using "u_{Go}" as the characteristic velocity scale, $2\,d_d\rho_L/3\,C_{Do}\rho_G$ as the characteristic length scale, and "c_o" as the characteristic particle concentration. Using these definitions, Equations 1, 3, and 5 become

$$-\frac{dc^*}{c^*} = \frac{Q_L\rho_L}{Q_G\rho_G C_{Do}}\frac{(1 - u_d^*)}{u_d^*}\eta dz^* \tag{6}$$

$$\eta = \left[\frac{(1 - u_d^*)K_{po}}{(1 - u_d^*)K_{po} + 0.7}\right]^2 \tag{7}$$

$$\frac{du_d^*}{dz^*} = \frac{(1 - u_d^*)^{1.5}}{2\,u_d^*} \tag{8}$$

The solution to Equation 8 is:

$$u_{dl}^* = 2[1 - x^2 + (x^4 - x^2)^{0.5}] \tag{9}$$

$$\text{where } x = \frac{3\,l_t C_{Do}\rho_G}{16\,d_d\rho_L} + 1 = (L + 8)/8 \tag{10}$$

By substituting Equations 7 and 8 into 6, we obtain:

$$\frac{dc^*}{c^*} = -\frac{2Q_L\rho_L}{Q_G\rho_G C_{Do}}\frac{(1 - u_d^*)^{1.5}}{\left(1 - u_d^* + \dfrac{0.7}{K_{po}}\right)^2} du_d^* \tag{11}$$

Upon integration we obtain

$$\frac{\ln Pt}{B} = \frac{\ln (c_l/c_o)}{B} = \frac{1}{K_{po}(1 - u_{dl}^*) + 0.7}$$
$$\times \left[4K_{po}(1 - u_{dl}^*)^{1.5} + 4.2(1 - u_{dl}^*)^{0.5} - 5.02\,K_{po}^{0.5}\right.$$
$$\left.\times \left(1 - u_{dl}^* + \frac{0.7}{K_{po}}\right)\tan^{-1}\left(\frac{(1 - u_{dl}^*)K_{po}}{0.7}\right)^{0.5}\right] - \frac{1}{K_{po} + 0.7}$$
$$\times \left[4K_{po} + 4.2 - 5.02\,K_{po}^{0.5}\left(1 + \frac{0.7}{K_{po}}\right)\tan^{-1}\left(\frac{K_{po}}{0.7}\right)^{0.5}\right] \tag{12}$$

$$\text{where } B = \frac{Q_L\rho_L}{Q_G\rho_G C_{Do}} \tag{13}$$

For venturi scrubbers with long throats, $u_{dl}^* \to 1$, and the first term in the right side of Equation 12 approaches zero.

Comparison of Model Predictions with Experimental Data

The model was compared with available experimental data. Figure 1 shows Ekman and Johnstone's (*3*) data for 1-μm diameter dibutyl phthalate (DBP) aerosols. The venturi scrubber used by Ekman and Johnstone was a small laboratory scale scrubber. The venturi throat was 3 cm in diameter and 3.8 cm long. The convergent and divergent angles were 25 and 7 degrees, respectively. Water was introduced in three ways: a single 32-mm jet injected downstream along the axis of the throat; radially outward from a brass pipe 32 mm in inside diameter with four 18.5-mm holes; and radially inward from a single 32-mm jet at the entrance of the throat. The data shown in Figure 1 are for radially inward and outward injection.

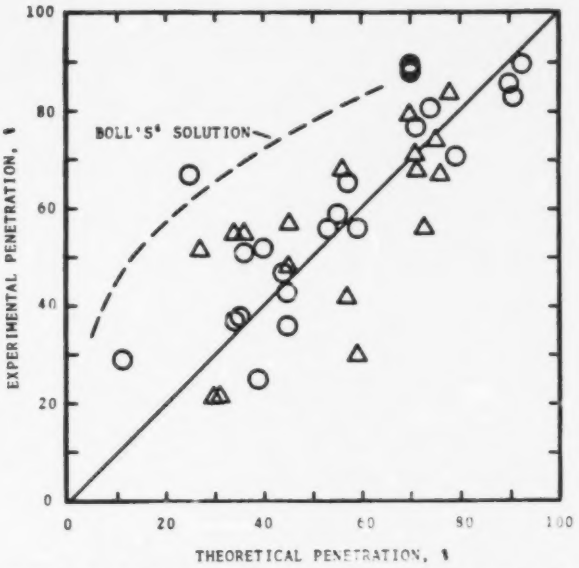

Figure 1. Comparison of Ekman and Johnstone's (*3*) data with theory presented (Equation 12) for penetration of 1-μm diam DBP through venturi scrubber
○ Radial outward liquid injection; △ radial inward injection

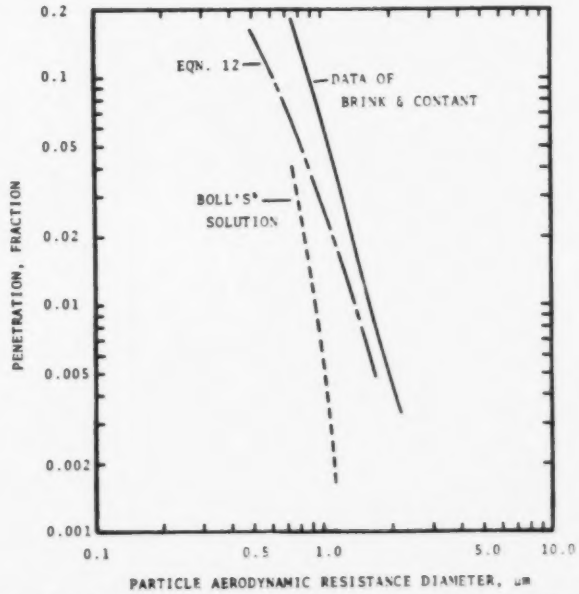

Figure 2. Comparison of Brink and Contant's (*12*) grade penetration data with theory for venturi scrubbers

As can be seen, the data are scattered. However, the average seems to agree quite well. The broken line in Figure 1 is the average predicted by Equation 1 as calculated numerically by Boll (*6*) taking into account the geometry of the scrubber. Equation 1 predicted too high an efficiency as revealed in this figure.

The scrubber used by Ekman and Johnstone was a small-scale laboratory scrubber. Because of the liquid coverage

problem, particle collection data from bench scale venturis are not reliable. Therefore, Equation 12 should be evaluated with large industrial scale venturi scrubbers.

Brink and Contant (*12*) and Calvert and Yung (*13*) reported performance test results on large industrial scale venturi scrubbers. The venturi scrubber tested by Brink and Contant was a Pease-Anthony venturi installed in a phosphoric acid plant. Figure 2 shows their curve along with theoretical predictions. The particle aerodynamic resistance diameter is used in this and the next figure. Raabe (*14*) supplies the following definition:

$$d_{pa} = \frac{d_p\sqrt{\rho_p C'}}{\sqrt{1\ \mathrm{g/cm^3}}} \qquad (14)$$

A particle density of 1.7 g/cm^3 (for P_2O_5) was assumed in the calculation.

As can be seen, the penetration predicted by Equation 12 is lower than the experimental data. However, compared with Equation 1, Equation 12 gives better predictions.

Calvert and Yung (*13*) measured the performance of an American Air Filter Kinepactor 32 venturi scrubber. Figure 3 shows the predicted and experimental fractional penetration curves. The experimental curves were calculated from simultaneous inlet and outlet cascade impactor data. The prediction agrees with the measurements.

Discussion

Equation 12 was derived from Equation 1 with some simplifying assumptions. Therefore, Equation 1 should give a better fit with experimental data than Equation 12. However, when compared with available experimental data, the reverse is true. This probably is caused by a nonuniform liquid drop distribution as speculated by Calvert (*1*) and Boll (*6*).

Figure 4 is a graphical presentation of the solution of Equations 9 and 12. Under a specific operating condition, the performance of the venturi scrubber depends on the throat length as revealed by Figure 4. The longer the throat, the more efficient the scrubber. This dependence is more profound for larger particles, i.e., larger "K_{po}". Thus, in designing a venturi scrubber, we should use a long throat. However, we should not use a longer throat then necessary because the pressure drop will increase with increasing throat length. The final choice

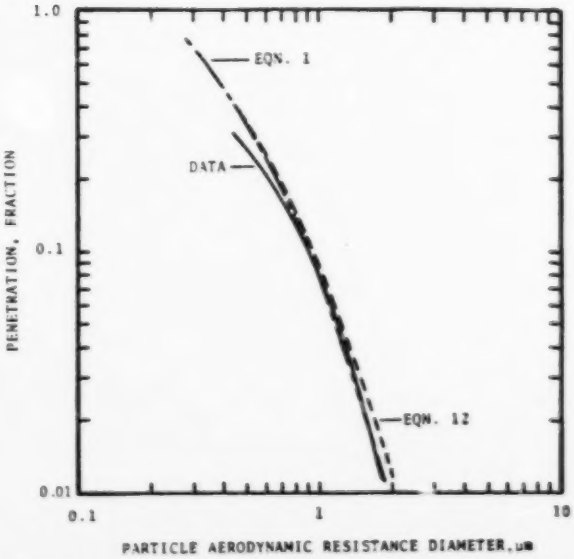

Figure 3. Comparison of Calvert and Yung's (*13*) data with theory for venturi scrubbers

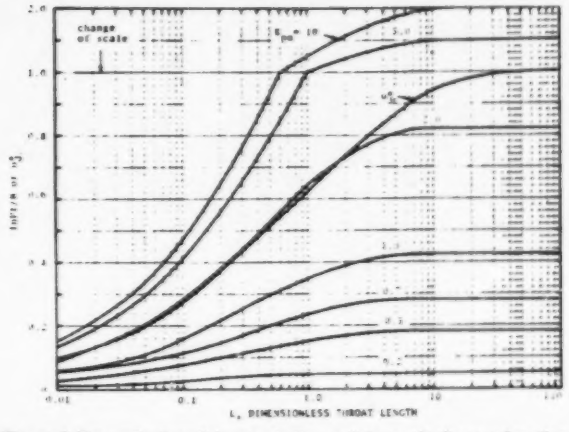

Figure 4. Theoretical particle penetration and drop velocity as a function of dimensionless throat length

of throat length should be a compromise of the two. A close inspection of Figure 4 reveals that a dimensionless throat length (L) of 2–3 would be sufficient. Further increase in dimensionless throat length will increase pressure drop with little gain in scrubber performance.

Nomenclature

B = dimensionless parameter characterizing liquid-to-gas mass flow rate ratio
C_D = drag coefficient, dimensionless
c = particle mass concentration, g/cm^3
c^* = c/c_o, dimensionless
d = diameter, cm or μm
d_{pa} = particle aerodynamic resistance diameter, μm (Equation 14)
K_p = inertial parameter, dimensionless
L = $3\,C_{Do}\rho_G l_t/2\,d_d\rho_L$, dimensionless throat length
l_t = venturi throat length, cm
N_{Re} = Reynolds number, dimensionless
Pt = particle penetration for particles with diameter d_p, fraction or percent
Q = volumetric flow rate, cm^3/s
u = linear velocity, cm/s
u^* = u/u_{Go}, dimensionless linear velocity
x = length parameter defined by Equation 10
z = axial coordinate, cm
z^* = $3\,C_{Do}\rho_G z/2\,d_d\rho_L$, dimensionless coordinate

Greek Letters

ρ = density, g/cm^3
μ = viscosity, poise
η = single drop collection efficiency, fraction

Subscripts

d = liquid drop
G = gas
L = liquid
l = at throat exit or distance "l_t" from throat entrance
p = particle
o = at throat entrance

Literature Cited

(1) Calvert, S., "Source Control by Liquid Scrubbers", in "Air Pollution", Arthur Stern, Ed., 2nd ed., Chap. 46, Academic Press, New York, N.Y., 1968.
(2) Calvert, S., *AIChE J.*, **16**, 392–6 (1970).
(3) Ekman, F. O., Johnstone, H. F., *Ind. Eng. Chem.*, **43**, 1358–63 (1951).
(4) Morishima, N., Yoshida, T., Kosoka, Y., Nonaka, Y., *Funtai Kogaku Kenkyu Kaishi*, **9**, 357–62 (1972).

(5) Dropp, L. T., Akbrut, A. J., *Tepoloenergetika*, **7**, 63–8 (1972).
(6) Boll, R. H., *Ind. Chem. Fundam.*, **12**, 40–50 (1973).
(7) Behie, S. W., Beeckmans, J. M., *Can. J. Chem. Eng.*, **51**, 430 (1973).
(8) Yung, S., Calvert, S., Barbarika, H. F., "Venturi Scrubber Performance Model", EPA 600/2-77-172, 1977.
(9) Calvert, S., Lundgren, D., Mementa, D. S., *J. Air Pollut. Control Assoc.*, **22**, 529–32 (1972).
(10) Nukiyama, S., Tanasawa, Y., in "Perry's Chem. Eng. Handbook", Perry and Chilton, Eds., 5th ed., McGraw-Hill, New York, N.Y., 1973.
(11) Hollands, K.G T., Goel, K. C., *Ind. Eng. Chem. Fundam.*, **14**, 16–22 (1975).
(12) Brink, J. A., Contant, C. G., *Ind. Eng. Chem.*, **50**, 1157 (1958).
(13) Calvert, S., Yung, S., "Evaluation of Venturi Scrubber", Final Rep. to EPA, Contract 68-02-1328, Task 6, Feb. 1975.
(14) Raabe, O. G., *J. Air Pollut. Control Assoc.*, **26**, 856–60 (1976).

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